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Empirical Study of Near Ground Propagation in Forest Terrain for Internet-of-Things Type Device-to-Device Communication

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ABSTRACT This paper presents continuous-wave power measurements conducted in forest terrain with a focus on path-loss in a device-to-device (D2D) communication scenario. The measurements are performed at 917.5 MHz with measurement ranges extending to more than 2.5 km, using a purpose-developed measurement system with a dynamic range of 180 dB. The impact of different antenna heights has been investigated by placing antennas at 1.5-, 2.5-, and 3.5-m elevation over the terrain. The measurements show that the antenna elevation in the given scenario has no significant impact on the received power. The measurements also show that the dominant path of propagation is through the foliage for the first approximately 1000 m, resulting in foliage excess loss being the dominant loss mechanism in this region. After approximately 1000 m, the measured received power tends to follow the fourth-power law, indicating that the dominant loss mechanism in this region is the distance-dependent path-loss. The measurement results have been compared to models proposed in the literature based on empirical data, as well as models proposed by ITU and COST. The comparison shows that only two models predicted the limit in the foliage excess loss in the measurement data. By applying these excess loss models in combination with path-loss models, it is possible to model the measured total path-loss with a root-mean-square error of less than 10 dB. This is achieved by either applying a model proposed by Tewari or a combination between the two-ray path-loss model and the ITU-R P.2108 clutter loss model.

INDEX TERMS Radio propagation, path-loss, excess loss, clutter loss, vegetation, foliage, forest, device-to-device (D2D), Internet-of-Things (IoT), narrow band IoT (NB-IoT), near ground propagation.

I. INTRODUCTION

As a part of the evolution towards the Next Generation Mobile Communication Network (5G), concepts such as Device-to-Device (D2D) communication and Internet-of-Things (IoT) are gaining interest [1]–[3].

D2D communication systems have the capability of communicating directly between devices and, thereby, not relying on a centralized network infrastructure as conventional cellular communication networks [4]. This capability is described in the standard for long term evolution-advanced (LTE-A) mobile communication, release 12, issued by the 3rd generation partnership project (3GPP) [5]. In this standard, the concept of long-range D2D is introduced as LTE Direct which is defined to support up to 1000 devices in a proximity range of 500 meters.

D2D communication is especially mentioned in relation to IoT, where small devices might not have the ability or the need to communicate with conventional cellular network infrastructure. A scenario where D2D communication and IoT could be used is a hiking trip with multiple participants. Here, a small device could exchange information about the location of the different participants, allowing everyone to keep track of the others for either competition or safety reasons. A method to implement this type of IoT communication is the so-called Narrow Band IoT (NB-IoT) which is included in Release 13 of LTE-A Pro by 3GPP [6].

Interest in coverage of rural areas for systems leads to an investigation of radio wave propagation in forests areas. The study of radio wave propagation in forest (vegetated) terrain has been of interest for decades [7]–[15]. The interest

started in the very high frequency (VHF) band [8]–[10], then extended to the ultra high frequency (UHF) band [8], [11]–[13] before being extended to the extremely high frequency (EHF) band [14], [15]. The measurements described in [14], together with others, are the basis for the International Telecommunication Unions Recommendation (ITU-R) P.833-9 for attenuation in vegetation in the frequency range from 30MHz to 100GHz [16].

The work presented in this paper gives attention to the UHF range, especially around 900 MHz. At the moment the frequencies here are generally used Global System for Mobile Communications (GSM), Universal Mobile Telecommunications System (UMTS) and LTE. LTE band 8 is located in the frequency range 880 - 960 MHz. The interest in this specific frequency range is due to the introduction of the so-called in-band D2D communication, which is foreseen implemented in e.g. LTE band 8 [2], [17].

The aim of this research is to study the expected communication range of an NB-IoT device, utilizing D2D communication. Since the devices in a Narrow Band Device-to-Device (NB-D2D) system are expected to be carried by users, the height of both the transmitting and receiving device is expected to be close to the ground. This means that the conventional base station (BS) to mobile station (MS) scenarios with an elevated BS cannot be used. Previous path-loss studies, close to the ground around 900 MHz, is presented in [18]–[20]. However, they do not extend to the full 164 dB path-loss, which is specified in the standard for NB-IoT [6].

This paper presents new measurements conducted with path-loss exceeding 164 dB at ranges of up to 2580 meters with near-ground antenna placement. The contribution of this work is, in addition to the new measurements in forested terrain, an overview of related measurements, existing theoretical and empirical models and their validity in the given scenario. Furthermore, the paper proposes a method for applying models resulting in the closest possible agreement to the measured data.

The paper is organized as follows. Section II presents related models and measurements. Section III describes the planning of the measurements, the measurement system and measurement scenario. Section IV presents the results and discusses the agreement with the existing models. Section V summarizes the work.

II. MODELS AND RELATED MEASUREMENTS

A. FUNDAMENTAL PATH-LOSS MODELS

Path-loss is defined as the reduction in the electric field strength after a given distance of transmission of an electromagnetic signal. In its simplest form this is given as $P_L = P_t - P_r$ in logarithmic units, where P_t and P_r are, respectively, the transmitted and received power. Note that the impact of antenna directivity (gain) is neglected in this section.

Free-space path-loss (FSPL) is given as (1) [21].

$$L_{FSPL} = 20 \log_{10} \left(\frac{4\pi d}{\lambda} \right) [dB] \quad (1)$$

where λ is the wavelength and d is the distance between transmitter and receiver.

In reality, free-space propagation is seldom found in terrestrial communication systems. The signal will, as a minimum, propagate along the ground. For distances up to a few tens of kilometres, the curvature of Earth can be neglected [22]. In this case, the path-loss can be approximated by the plane earth propagation model as seen in (2).

$$L_{PE} = 20 \log_{10} \left(\frac{d^2}{h_{tx} h_{rx}} \right) [dB] \quad (2)$$

where h_{tx} and h_{rx} denote the height of the transmit (Tx) and receive (Rx) antenna.

Equation (2) is also known as the two-ray model and it should be remarked that the approximation is only valid when the height of the transmitting and receiving antenna is small compared to the distance between transmitter and receiver [22]. For this reason, a piecewise linear model is often applied as shown in (3).

$$L_{2Ray} = \begin{cases} L_{FSPL}, & d < d_c \\ L_{PE}, & d \geq d_c \end{cases} [dB] \quad (3)$$

where d_c denotes the crossing distance, which can be approximated by (4).

$$d_c = \frac{4\pi h_{tx} h_{rx}}{\lambda} \quad (4)$$

As seen in (3) the rate of path-loss is first given by FSPL, proportional to d^{-2} until the cross distance (d_c), after which the rate of loss can be found to be proportional to d^{-4} . The increased rate of loss is a result of destructive interference from the signal reflected by the ground [22].

The different rates of path-loss are represented by the so-called path-loss exponents, with 2 as the default value for free-space. However, as shown by the two-ray model, it is often convenient to manipulate the path-loss exponent to fit other scenarios. As a result, the expression (1) is often expanded to include also a parameter for the path-loss exponent as in (5). This model is sometimes denoted as the log-distance or the simplified path-loss model [23].

$$L_{PL} = 20 \log_{10} \left(\frac{4\pi d_0}{\lambda} \right) + \gamma 10 \log_{10} \left(\frac{d}{d_0} \right) [dB] \quad (5)$$

where the first term describes the loss at a specified reference distance denoted by d_0 and γ is the path-loss exponent. The value of the path-loss exponent is usually in the range of 1.5 to 6.5 and is estimated for the different scenarios based on empirical studies.

The first term in (5) can be seen as the fundamental loss due to power dissipation, while the second is the distance term where the loss is weighted by the path-loss exponent. Adjusting the path-loss exponent is one way of fitting a model/approximation to an empirical data set.

The total path-loss can be expressed as a sum of the FSPL and an extra loss often denoted as excess loss, excess path-loss or excess propagation loss.

B. TERRAIN LOSS AND ANTENNA HEIGHT GAIN

The fundamental path-loss models assume either line-of-sight or a plane earth. However, as noted in [24], placing the transmit and receive antennas close to the ground introduces further losses, when the antenna heights are low as compared to the measurement distance and/or shifts in terrain topography. Egli [24] modeled this as a combination of the basic propagation loss as defined in (3) together with an excess terrain loss as seen in (6).

$$L_{Egli} = L_{2Ray} + 20 \log_{10} \left(\frac{f}{40} \right) [dB] \quad (6)$$

where f [MHz] is the frequency.

A widely known and used model, including the terrain and antenna heights is the Okumura model including the Hata and COST-231 extensions. The models are, however, not suitable for this work as one of their limitations is the height of the basestation antenna, has to be above 30 m. Furthermore, at least one of the antennas has to be placed higher than the surrounding rooftops/clutter [25]. Efforts by Erceg et. al. [26] have been made in order to apply the model to antennas surrounded by clutter, but the proposed model is valid only if the basestation antenna is placed at a height between 10 m and 80 m which again is not the case for the study presented in this work.

ITU has also provided multiple models for terrestrial path-loss. The recommendations P.370, P.529 (modified Okuma-Hata model) and P.1146 all covered similar scenarios, which is the reason that they in 2001 were superseded by P.1546 (Method for point-to-area predictions for terrestrial services in the frequency range 30 MHz to 3000 MHz) [27]. The model is based on graphs of field strength predictions for ranges from 1 to 1000 km, antenna heights from 10 to 1200 m and the frequencies 100, 600 and 2000 MHz. The current version (P.1546-5) further contains methods for extrapolation and interpolation to cover the range from 1 to 1000 m, lower placements of the antennas and other frequencies. These methods for extending the model range are quite cumbersome and are therefore not described in this text. The reader can instead refer to [27, Annexes 5 and 6]. In short, the field strength predictions have been interpolated between under and overlying frequencies, followed by correction for the Tx and Rx heights. Lastly, they have been extrapolated to cover the range from 1 to 1000 m. The predicted path-loss is finally bounded by the FSPL to avoid discontinuity. With these extensions the model is able to describe the path-loss along the terrain but does not include foliage loss.

An empirical model for path-loss including both the terrain and foliage loss has been proposed as in (7) by Tewari et. al [28]. The model has only been verified in the frequency range from 50 to 800 MHz, considering distances up to 4000 m and antenna elevations between 1.5 m and 16.5 m. However, it is included here as the validity range is

TABLE 1. Empirical values for Tewari model [28].

Frequency [MHz]	Polarization	α_2	A_2	B_2
50	Horizontal	-	0	7.3670
200	Horizontal	0.0110	0.8201	5.0450
500	Horizontal	0.0138	0.6571	1.4304
800	Horizontal	0.0152	0.4491	0.6291
50	Vertical	-	0	1.9170
200	Vertical	0.0125	0.4989	1.8358
500	Vertical	0.0135	0.3658	0.9040
800	Vertical	0.0140	0.2661	0.5331

close to that of interest in this work.

$$L_{Tewari} = -27.56 + 20 \log_{10}(f) - 20 \log_{10} \left(\frac{A_2 \exp(-\alpha_2 d)}{d} + \frac{B_2}{d^2} \right) [dB] \quad (7)$$

where f [MHz] is the frequency and d [m] is the propagation distance. α_2 [dB/m] is the attenuation rate, A_2 and B_2 are empirically found constants, given in TABLE 1.

Neither the Egli or Tewari model considers the height of the Tx and Rx antennas. However, as seen from e.g. the plane earth model, the height of the antennas above terrain can have a significant impact on the predicted path-loss. This impact is sometimes modelled as a so-called height gain [29], [30]. Tewari et al. [31] has also proposed a height gain extension to his model as seen in (8).

$$G_h = 12 + 4 \log_{10}(f) - 20 \log_{10}(h_{tx} h_{rx}) [dB] \quad (8)$$

where f [MHz] is the frequency and h_{tx} and h_{rx} [m], respectively, denotes the height above terrain for the transmitting and receiving antenna.

The height gain expressed in (8), together with the path-loss model defined in (7), can be used to model the total path-loss as (9) [31].

$$L_{Tewari_WG} = L_{Tewari} + G_h [dB] \quad (9)$$

In the literature the so-called path-specific models have also been presented. The example presented in [32] is based on the integral equation and the one in [33] on the geometrical theory of diffraction (GTD). However, for this work these computationally heavy models have not been further investigated.

A comparison between the discussed terrain loss models is presented in Fig. 3. Two different heights of the Tx and Rx antenna have been used: Tx 3.5 m to Rx 2.5 m and Tx 1.5 m to Rx 1.5 m. This allows to illustrate the height gain characteristics of the different models. As a reference, the FSPL (1) and two-ray model (3) have also been plotted in Fig. 3.

From Fig. 1 it is clear that the predicted path-loss of the Egli model changes only due to the underlying two-ray model. The predicted loss of the ITU P.1546 model for both elevation combinations of the antennas is very close to the two-ray models prediction for 1.5 m to 1.5 m scenario. The difference in predicted loss between the two antenna elevation combinations is almost constant throughout the plotted distance.

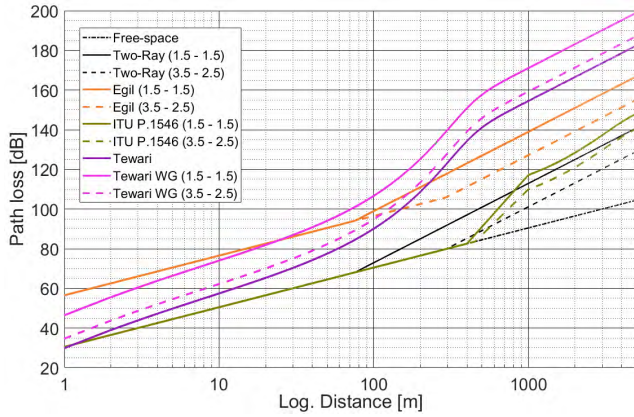


FIGURE 1. Comparison between terrain path-loss models using the following parameters: $f = 800$ MHz, $h_{tx} = \{1.5 \text{ m}, 3.5 \text{ m}\}$ and $h_{rx} = \{1.5 \text{ m}, 2.5 \text{ m}\}$.

This is also the case for the Tewari model and is a result of the added height gain. The predicted path-loss of the Tewari model is clearly different, depending on the antenna heights. In fact, if the height of the Tx and Rx antenna is raised further the model would, at some point, predict a path-loss lower than FSPL. This indicates that it would need to be bounded by this threshold as in the ITU P.1546 model.

C. FOLIAGE-LOSS MODELS

Radio wave propagation in forest environments is divided into three different categories: direct, reflected and lateral waves [9]. The direct and reflected waves are going through the vegetation and are therefore subject to an increased loss due to scattering and absorption from the foliage. The lateral waves propagate from the transmitter through the tree crowns, over the top of the vegetation and then back down through the vegetation to the receiver. In [9] and [18] it is concluded that, at frequencies close to 900 MHz, the dominant propagation mechanism at ranges up to 1000 m is through the vegetation, hereafter direct and reflected waves are dominant. Due to this, the total path-loss has to include the excess vegetation- or foliage-loss.

Empirical excess loss models for horizontal propagation in vegetated areas known as exponential decay (EXD) models are dating back to the 1960s [7], [34]. These models together with the modified exponential decay (MED) models are in the form shown in (10) [35].

$$L_{MED} = A f^B D^C \text{ [dB]} \quad (10)$$

where A , B and C are fitted values for respectively amplitude, frequency and distance dependency. f is the frequency and D is the distance of propagation in the vegetation.

An overview of the different fitted values is given in TABLE 2 for different versions of the model. The original EXD parameters are modified to the MED parameters based on a proposal by Weissberger after a review of various measurements in the frequency range from 200 MHz to 95 GHz [35]. The ITU-R 235-6 model (at that time CCIR)

TABLE 2. Empirical values for MED models.

Model	A	B	C	Condition(s)
Lagrone [34]	0.26	0.77	1	$100 \leq f \text{ [GHz]} \leq 3200$
Weissberger [35]	1.33	0.284	0.588	$14 < D \text{ [m]} \leq 400$
	0.45	0.284	1	$0.23 \leq f \text{ [GHz]} \leq 95$ $0 < D \text{ [m]} < 14$ $0.23 \leq f \text{ [GHz]} \leq 95$
ITU-R 235 [36]	0.2	0.3	0.6	$0 < D \text{ [m]} < 400$ $200 \leq f \text{ [MHz]} \leq 95000$
COST235 [37]	26.6	-0.2	0.5	out-of-leaf $200 \leq f \text{ [MHz]} \leq 95000$
	15.6	-0.009	0.26	in-leaf $200 \leq f \text{ [MHz]} \leq 95000$
FITU-R [38]	0.37	0.18	0.59	out-of-leaf $200 \leq f \text{ [MHz]} \leq 95000$
	0.39	0.39	0.25	in-leaf $200 \leq f \text{ [MHz]} \leq 95000$

TABLE 3. Empirical values for MA model [16].

Frequency [MHz]	A_1 [dB]	α_1 [-]	Condition(s)
900 - 1800	0.18	0.752	Tropical trees (height 15 m) $h_{rx} = 2.4 \text{ m}$
900 - 2200	1.15	0.43	Mixed forest (height 15 m) $h_{tx} = 25 \text{ m}$ and $h_{rx} = 1.6 \text{ m}$
105.9 - 2117.5	1.37	0.42	Mixed forest (height 14 m) $h_{rx} = 1.5 \text{ m}$

is further tuned to measurement campaigns conducted at 30 MHz to 30 GHz and the FITU-R model is fitted to measurements conducted at 11.2 and 20 GHz. The COST 235 model is fitted to measurements conducted at 9.6 and 57.6 GHz.

The exponential decay models are purely based on empirical measurements and, as pointed out by Seville and Craig [39], are not bounded by fundamental propagation mechanisms. Due to this, a semi-empirical model, as shown in (11) was proposed. This model known as the Maximum Attenuation (MA) model is the current ITU recommendation (P.833-9) for attenuation in vegetation from 30 MHz to 100 GHz [16].

$$L_{MA} = A_m \left[1 - \exp \left(\frac{-D \xi}{A_m} \right) \right] \text{ [dB]} \quad (11)$$

where A_m [dB] is the maximum attenuation and ξ $\left[\frac{\text{dB}}{\text{m}} \right]$ is the specific attenuation for a very short vegetative path, both given for a specific type of vegetation. D [m] is the distance of propagation in the vegetation.

The two vegetation type specific parameters; maximum attenuation and specific attenuation, are determined based on empirical studies. This implies that they both are also frequency dependent. The dependency of the maximum attenuation is expressed as (12).

$$A_m = A_1 f^{\alpha_1} \text{ [dB]} \quad (12)$$

where f [MHz] is the frequency and A_1 and α are empirical determined values as shown in TABLE 3.

Empirically found values have been used to create Fig. 2 for the specific attenuation. This is used to determine values

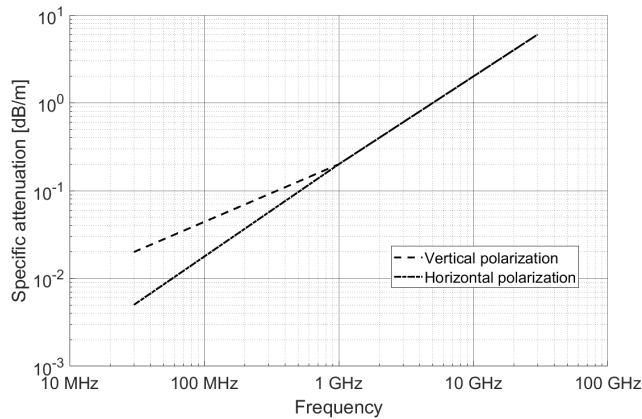


FIGURE 2. Specific attenuation due to woodland [16].

for the MA model (11) dependent on the frequency. It can be noted in Fig. 2 that the specific attenuation is polarization sensitive at frequencies below 1 GHz.

Previously, a further extension of the MA model, denoted the nonzero gradient (NZG) model, was recommended by the ITU for frequencies above 5 GHz [40]. The model, as shown in (13), was developed by Seville and Craig [39] and was also included in a slightly different form in the COST235 report [37].

$$L_{NZG} = R_{\infty}d + k \left[1 - \exp \left(-\frac{(R_0 - R_{\infty})D}{k} \right) \right] \text{ [dB]} \quad (13)$$

where R_{∞} is the final gradient of the attenuation curve, R_0 is the initial gradient and k is the offset of the final gradient. All of these parameters are again found by empirical studies.

The general values, suggested by Seville et al., for the NZG model are given in TABLE 4.

Other semi-empirical foliage-loss models have been proposed based on various measurements. Most of these models have a high similarity to the ones presented previously. For most of these models, the fitting is done for short distances or very specific scenarios. The aim of this paper is to explore the applicability of the presented models over long distances which, to the best of our knowledge, has not been investigated yet. As a result more of these semi-empirical models have been excluded in this paper.

ITU defines clutter as all objects on the surface of the earth interfering with the radio propagation and as a consequence, the vegetation can be considered clutter. The resulting clutter loss can be modelled by the ITU-R P.2108 clutter loss model, where the median is given as (14) [42].

$$L_C = -5 \log \left(10^{-0.2L_l} + 10^{-0.2L_s} \right) \text{ [dB]} \quad (14)$$

$$L_l = 23.5 + 9.6 \log(f) \text{ [dB]} \quad (15)$$

$$L_s = 32.98 + 23.9 \log(D) + 3 \log(f) \text{ [dB]} \quad (16)$$

where f [GHz] is the frequency and D [km] is the propagation distance in clutter.

More theoretical models for propagation through vegetated areas based on statistics have been proposed in e.g [43]–[45].

TABLE 4. Empirical values for NZG model [41].

Frequency [GHz]	R_{∞}	R_0	k
1.3	0.1	1.15	14
2	0.1	1.4	13
11.6	0	3.1	30

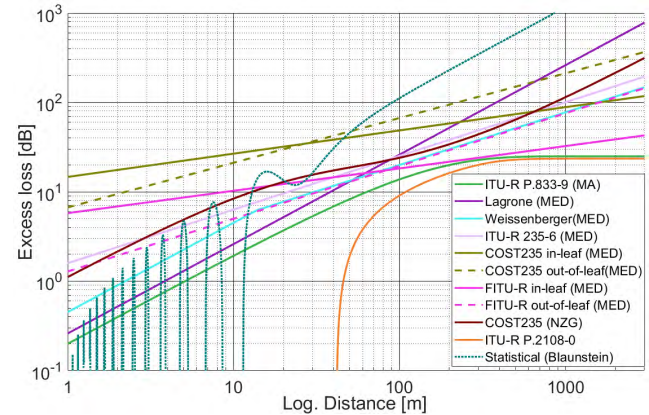


FIGURE 3. Comparison between excess loss models for woodland using the following parameters: $f = 1$ GHz, $A_1 = 1.37$, $\alpha = 0.42$, $R_{\infty} = 0.1$, $R_0 = 1.15$, $k = 14$, $\Theta = 0.5$, $h_{tx} = h_{rx} = 1.5$, $\Delta = 0.6$ and $\rho = 0.7$.

Reference [45] is based on Twersky's approximation of multiple scattering of arbitrary configurations [46]. The model is developed for excess losses in a forest environment and a simplified version valid for frequencies above 300 MHz and ranges up to 12 km is included in (17).

$$L_{stat} = -10 \log_{10} \left[\exp(-\theta_0 D) \times \left(\frac{\Theta}{2} + 4 \sin^2 \left(\frac{2\pi h_{tx} h_{rx}}{\lambda D} \right) \right) \right] \text{ [dB]} \quad (17)$$

where λ is the wavelength, D is the propagation distance in foliage, and h_{tx} and h_{rx} , respectively, denotes the height above terrain for the transmit (Tx) and receive (Rx) antenna. Θ is the absolute value of the reflection coefficient for the trees. θ_0 is the one-dimensional tree density parameter given by (18).

$$\theta_0 = \frac{2\langle\Delta\rangle\rho}{\pi} \text{ [m}^{-1}\text{]} \quad (18)$$

where $\langle\Delta\rangle$ [m] is the average diameter of the trees and ρ [m⁻²] is the average tree density.

Due to the general need for detailed information about the vegetation when utilizing the statistical models they are not explored further.

A comparison of the presented excess loss models is presented in Fig. 3. Only the statistical model (17) is non-monotonic until approximately 25 m caused by the embedded sinusoidal function. There are two models where the predicted excess loss reaches an extremum. These are the ITU P.833-9 and ITU P.2108-0 which both reach the extremum at approximately 500 m. Some models quite fast predict extreme excess loss due to their monotonically increasing behaviour. This is even clearer at large distances as shown

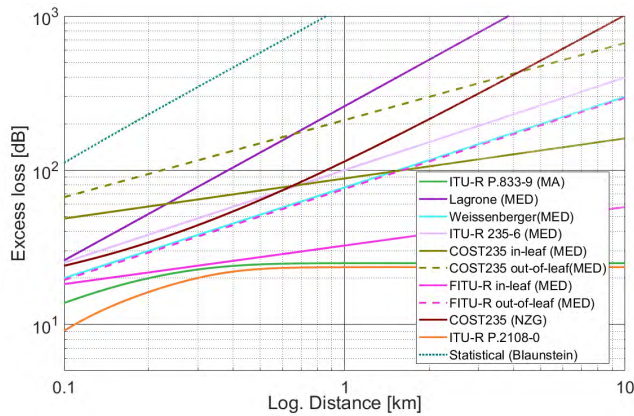


FIGURE 4. Comparison between excess loss models between 0.1 and 10 km for woodland with same parameters as in Fig. 3.

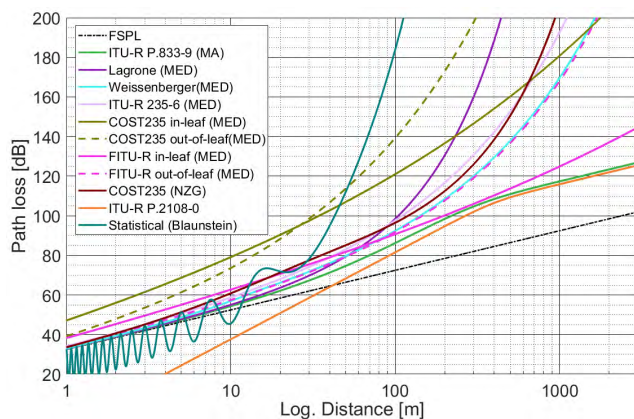


FIGURE 5. Comparison between excess loss models added with FSPL using same parameters as in Fig. 3.

in Fig. 4. Most of the models are based on empirical data for only short distances of propagation in the foliage which might explain this behaviour. The validity of these models at long distances can be argued but have nevertheless not been addressed in most literature. As a result, they have been included here to illustrate their limitations.

From Fig. 5 it is possible to compare the excess foliage loss models when added with FSPL (1). Most of the models are similar until approximately 100 m, where after some predict rapidly increasing path-loss.

III. MEASUREMENT CAMPAIGN

To investigate the application of D2D communication in a forest hiking scenario, a measurement campaign was performed. The objective is to investigate the long range propagation defined as a distance with path-loss exceeding 164 dB as given by the standard for NB-IoT [6]. The measurement was performed with terminals placed at low heights and operating at a frequency in LTE band 8.

A. RELATED MEASUREMENTS

Numerous previous measurements have been conducted and documented in the literature, as seen from the number of

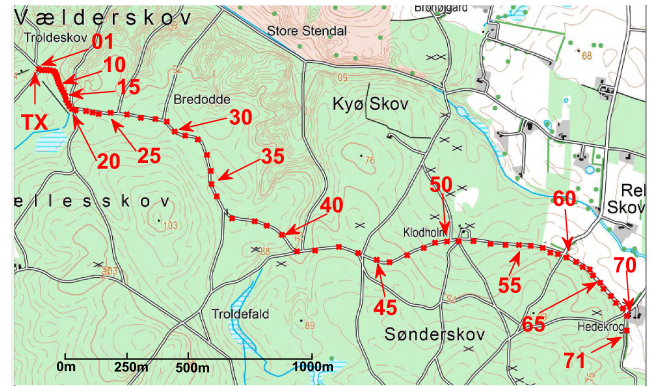


FIGURE 6. Measurement locations. Tx position is marked at the left top in the figure. Map source: [56].

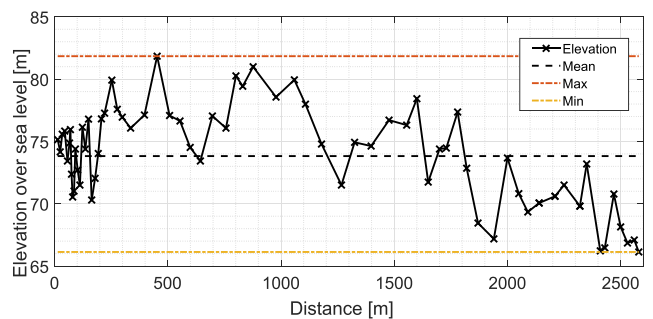


FIGURE 7. Terrain elevation over sea level versus straight line distance to the Tx.

presented empirical models. A summary of the related measurements is listed in TABLE 5, showing that none of the related measurements fully covers the objective of this study.

B. MEASUREMENT LOCATION

A forest located south of the city of Aalborg in Denmark called Rold Skov was chosen for the measurement. The forest consists of a mix of coniferous and deciduous trees. A map of the forest is shown in Fig. 6 with the 71 measurement positions.

The measurement positions are recorded using surveyor grade equipment, as explained in [55], resulting in an accuracy of the positioning for the majority of the positions within a few centimetres. However, due to the foliage coverage at some locations, the combined maximum uncertainty have been defined as less than 0.15 m in the plane and 1 m in elevation. The measurement points have been distributed such that they are most dense close to the transmitter (Tx) and at the furthest measurement positions. The furthest measurement position is 71 where the straight line distance to Tx is 2580 m.

The recorded terrain elevations have been plotted for the 71 measured positions in Fig. 7. Data is only recorded at the 71 defined positions, marked with crosses in Fig. 7, meaning that the line between the measurement positions is added only to aid readability. It can be seen in Fig. 7 that the variations in terrain elevation are restricted to ± 8 m from the mean elevation.

TABLE 5. Summary of related measurements.

Environment	Frequency [MHz]	Tx Height [m]	Rx Height [m]	Max. Range [m]	Max. Loss [dB]	Ref.
Coniferous, Deciduous and a mix of the two type forest.	146, 390, 961 and 1900	3, 6 and 12	2.5	3000	110	[19]
Deciduous forest.	922 and 2466	1.5	1.5	600	130	[20]
Scrub-land	920 and 2400	1.5	1.5	50	45	[47]
Palm Plantation	240 and 700	2.15	2.15	1000	140	[48]
Deciduous Forest with and without leaves. Grass- and scrub-land	2400, 3500 and 5800	0.9, 1.2 and 1.6	0.9, 1.2 and 1.6	110	120	[49]
Coniferous Forest	900, 1800 and 2100	2	2	400	50	[50]
Coniferous, Deciduous and a mix of the two type forest.	2400	1.8	1.8	1028	110	[51]
Deciduous Forest with and without leaves.	300 and 1900	0.75, 1.15 and 1.55	0.75, 1.15 and 1.55	500	160	[52]
Deciduous Forest and brush-land.	830-4200	1.3	1.3	50	90	[53]
Light trees and scrub-land	3500	0.3 and 2.1	2.1	40	100	[54]

TABLE 6. Measurement system parameters.

Parameter	Setting
Center Frequency	917.5 MHz
Resolution bandwidth (RBW)	1 kHz
Sweep Points	501
Sweep Time	5 s
Detector Mode	Root Mean Square (RMS)
Dynamic Range	180 dB

C. MEASUREMENT SYSTEM

The aim of this work is to study the long-range path-loss of an NB-D2D system. Therefore a path-loss exceeding the 164 dB is measured as specified in the standard for NB-IoT [6]. This requires the measurement system to have a large dynamic range. As a result, a purpose-developed system has been developed as described in detail in [55]. A brief description is included in the following and summarized in TABLE 6.

A test signal is generated as a single tone continuous wave at 917.5 MHz. The signal is amplified and transmitted at 40 dBm using a 5 dBi folded monopole antenna. A power meter is constantly recording the RF-power level just before the antenna port through a coupler. The recorded Tx power level is used to determine the correct path-loss between the Tx and Rx antenna. The Rx antenna is a 1 dBi dipole. After the antenna, a bandpass filter is placed before an LNA, which ensures that the test signal can be recovered and measured. The test signal is measured at the Rx position over a period of 5s using a spectrum analyser, while moving the antenna around in a circle with a diameter of 35 cm. The movement of the antenna allowed 501 snapshots of the power level to be distributed along the radius of the circle. As the circle radius corresponds to at least one wavelength of the recorded frequency, it is possible to mitigate multipath fading by averaging in the spatial domain. As a result, the recorded RF-power level for the given measurement point is an averaged value.

The measurement campaign was performed with two antenna height combinations, resulting in two datasets.

The first consisted of both the transmitting and receiving antenna placed on a mast 1.5 m above terrain. For the second the transmitting antenna was on a 3.5 m mast, while the receiving antenna was positioned on a 2.5 m mast. Throughout both measurement campaigns, the transmitting antenna mast was kept static, while the receiving antenna mast moved to the measurement positions. At each measurement position, the spectrum analyser was re-tuned to the test signal frequency to correct any offset between the asynchronous oscillators of the signal generator and spectrum analyser.

IV. RESULTS

For the Tx 1.5 m to Rx 1.5 m antenna elevation combination the dataset consists of a total of 265 measurements, whereas the dataset for the Tx 3.5 m to Rx 2.5 m antenna elevation combination consists of 106 measurements. Both datasets contain repetitions at selected measurement positions, which is why the total number of measurements is larger than the number of measurements positions. Each of the measurements was conducted as a 5s sweep, recording a total of 501 power sweep points. As each sweep point is an individual power measurement, the power for a given measurement position is found as the average of the total amount of individual sweep points. This means that, for measurement positions with only one measurement, 501 sweep points are averaged, while positions with e.g. 3 measurements utilize 1503 sweep points for the averaging. Note that, before the concatenation of the sweep points, each power reading has been corrected by using known values of the measurement systems gains and losses as described in [55].

The received power for the measurement positions is shown in Fig. 8 as a solid line for the mean power and whiskers indicating the variance of all the measurement points for the given position.

Fig. 8 shows that the received power is predicted quite well until approximately 200 m with the simple Two-Ray model (3). This corresponds to the fact that the measurement route is quite open resulting in almost line-of-sight (LOS)

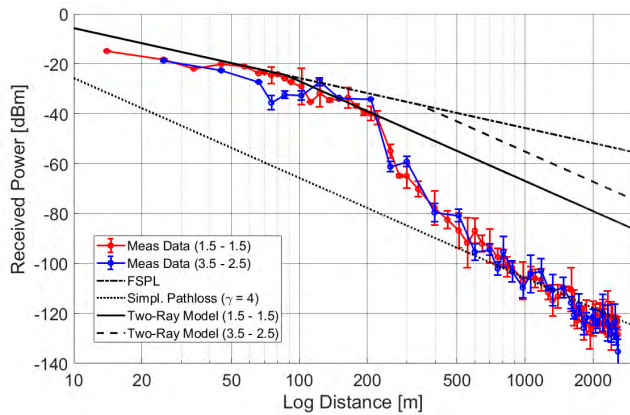


FIGURE 8. Received power for both measurement datasets plotted with the simplified path-loss model (5) as well as the Two-Ray model (3) for comparison.

until this point. After this, the forest gets denser which in the measurements can be seen as a rapid decrease in received power. From approximately 800 m until the furthest measurement at 2580 m the received power can be fairly well predicted using the the simplified path-loss model (5) with $\gamma = 4$. The transition from 200 m to approximately 800 m is assumed to be caused by the excess loss due to the foliage.

A. MODEL COMPARISON

To further study the measurement data, a comparison the models presented in Sec. II has been made. The first comparison is to the path-loss models presented in Sec. II-B. In Fig. 8 it is found that the two antenna height combinations show almost identical behaviour. This means that the very different predicted path-loss dependent on antenna height by the Tewari height gain model (8) seems not to fit at the chosen antenna heights. It can also be seen that the close fit with FSPL for the first part of the measurement data means that the constant additional loss given in the Egli model (6) will result in an overestimation of the path-loss in this region. As a consequence, it is chosen only to plot the measurement data together with the original Tewari model (7) and the ITU-R P.1546 model as shown in Fig. 9.

In Fig. 9 it is clear that the model with the best fit is the Tewari model (7). Which is here used with the values for 800 MHz, as given in TABLE 1, while the measurement was conducted at 917.5 MHz. This means that the resulting comparison should be treated with some caution.

As explained in Sec. II-C the foliage introduces excess loss which should be added to the path-loss for a given path to express the total loss. By comparing the foliage model, when combined with FSPL as shown in Fig. 5, to the measured path-loss as seen in Fig. 9, it is clear that some of the models highly overestimate the path-loss. As a result, only the models which seem to predict reasonable losses also after 1000 m have been included in the following comparisons. The chosen models are:

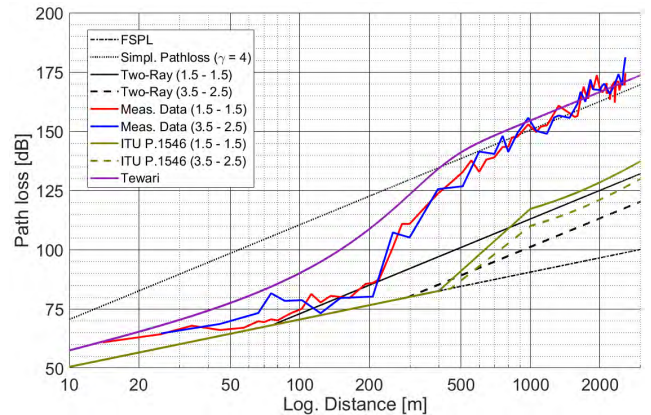


FIGURE 9. Comparison between terrain path-loss models and measurement data.

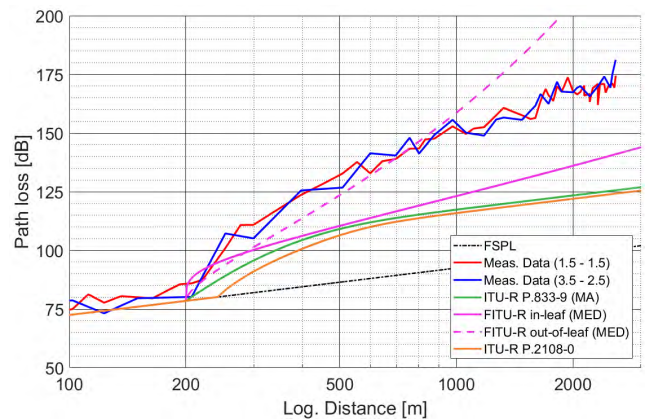


FIGURE 10. Comparison between foliage excess loss models added with FSPL and measurement data.

- ITU-R P.833-9
- FITU-R
- ITU-R P.2108-0

For all the models in the comparison, the excess losses due to foliage have only been modelled from 200 m and onwards, following the observations from Fig. 8.

For the comparison presented in Fig. 10 the foliage models have been added with FSPL. It is clear that the ITU-R P.833-9 and ITU-R P.2108-0 models are underestimating the path-loss when only combined with FSPL. It seems that the FITU-R out-of-leaf is able to predict the loss until approximately 1000 m, whereafter it is overestimated. The FITU-R in-leaf is like the two other models underestimating the path-loss which could indicate that the losses due to the terrain are not modelled sufficiently or they simply underestimate the foliage loss.

To compare the performance of the chosen foliage models in combination with different terrain/path-loss models Fig. 11 and 12 have been included. The two figures show respectively the combined path-loss between the two-ray model and the ITU-R P.1546 model. The FITU-R out-of-leaf has not been included here, since from Fig. 10 it is clear that it would over-

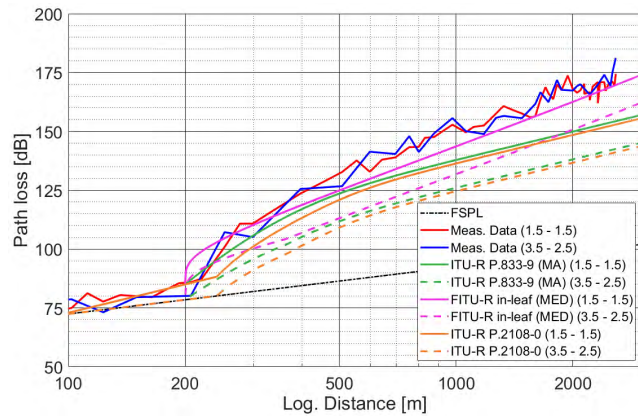


FIGURE 11. Comparison between foliage excess loss models added with the two-ray path-loss model and measurement data.

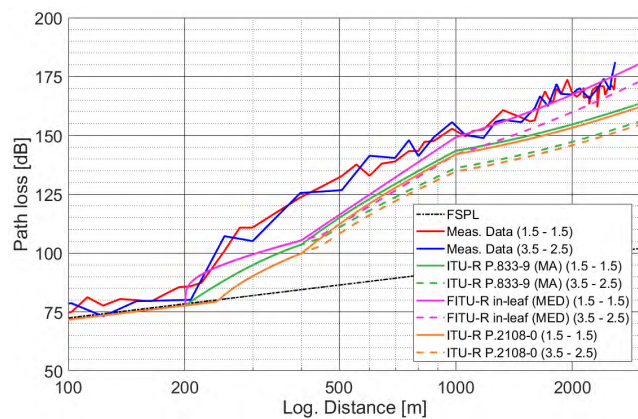


FIGURE 12. Comparison between foliage excess loss models added with the ITU-R P.1546 model and measurement data.

estimate the total path-loss, when added with terrain/path-loss models, giving higher losses than FSPL.

The measurement data does not show a significant difference between two height scenarios. This means models resulting in only a small difference in the predicted height gain is to be preferred. For the foliage loss predicted by the ITU-R and FITU-R models added with the two-ray model, as shown in Fig. 11, the offset at 1000 m between the estimated total path-loss for the two height scenarios is 11.8 dB. For the foliage loss added with the ITU-R P.1546 model in Fig. 12 the offset is 7.3 dB.

As seen in Fig. 11, the additional path-loss predicted by the two-ray model is not enough to match the measured path-loss. The FITU-R in-leaf models are suitable for the Tx 1.5 m to Rx 1.5 m scenario. As the FITU-R is fitted to measurements conducted at 11.2 and 20 GHz, it is assumed that the fit relatively good with the measurements presented here is due to the significant losses observed at those higher frequencies, which might compensate the higher losses expected for these measurements, due to low antenna elevation.

The higher than the two-ray model predicted path-loss of the ITU-R P.1546 model, shown in Fig. 12, is still not enough

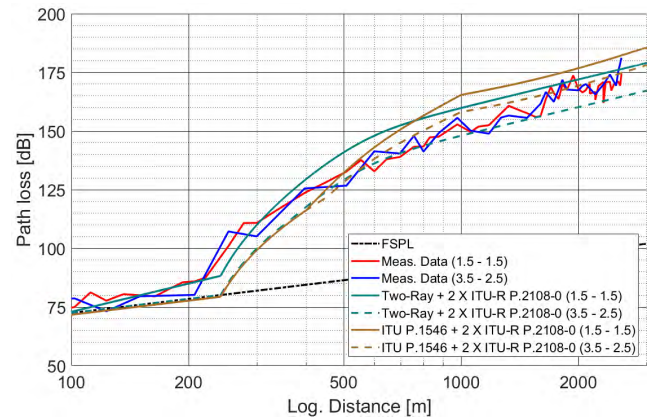


FIGURE 13. Comparison between measurement data and two times clutter loss added with the two-ray or ITU-R P.1546 model.

for the combined path-loss to reach the measured path-loss. This is especially clear in the region from 200 to 1000 m.

In the performed measurement both the Tx and Rx are surrounded by foliage. Hence, an improved match might be obtained by adding two times the excess loss predicted by the ITU-R P.2108-0 clutter loss model with the path-loss models. The resulting predicted total path-loss is presented in Fig. 13.

It is from Fig. 13 quite clear that applying these kind of models will result in the best prediction throughout the measurement range. It can be discussed if applying two times clutter loss is correct but, nevertheless, it gives an improved prediction for the measurement scenario.

B. MODEL PERFORMANCE

An overview of the performance of the different model combinations is given by computing the root mean square (RMS) error.

The RMS error has been computed in dB as shown in (19).

$$E_{RMS} = \sqrt{\frac{\sum_{i=1}^N (E_i^2)}{N}} \text{ [dB]} \quad (19)$$

where N is the total number of measurements, E_i is the difference between the measured and predicted path-loss of the i th measurement.

The RMS errors for the combinations between path-loss and foliage excess loss models are shown in TABLE 7 for both the low (L) and high (H) antenna height combination.

TABLE 8 shows the RMS error between the Tewari model and the measurement data. Both the RMS value for the entire measurement distance, as well as only from 200 m, have been included for comparison with the values in TABLE 7.

By investigating TABLE 7 and TABLE 8 it can be found that the best performing model in the low scenario is the FITU-R in-leaf. However, this model results in a large RMS error for the high scenario. If both of the height scenarios are considered the best performing model is the Tewari model when only applying it after 200 m. The overall best

TABLE 7. RMS error foliage models [dB].

Model		FSPL	Two-Ray	ITU-R P.1546
ITU-R P.833	L	36.9	14.3	12.3
	H	37.6	26.4	19.0
FITU-R in-leaf	L	27.2	5.9	7.1
	H	28.3	17.5	10.9
FITU-R out-of-leaf	L	32.1	-	-
	H	28.9	-	-
ITU-R P.2108	L	38.5	15.8	14.3
	H	39.2	28.1	20.8
2 X ITU-R P.2108	L	-	7.6	11.2
	H	-	8.1	6.5

TABLE 8. RMS error Tewari [dB].

Model		All Meas. Data	From 200 m
Tewari	L	10.2	6.7
	H	9.5	7.6

performing model is found to be the two-ray model in combination with two times clutter loss.

V. CONCLUSION

This paper presents a measurement campaign conducted over a long range in a forest environment with low elevation antennas. The measurement data have been compared with existing foliage excess loss models as well as relevant path-loss models. This has been done in order to investigate appropriate models for determining the expected range for IoT type D2D communication systems in rural areas.

The measurement data shows that the measured path-loss tend to follow the fourth-power law after approximately 1000 m. This finding agrees with the conclusion by Egli for frequencies between 90 and 1000 MHz [24]. Furthermore, there is also correspondance with [9] and [18], where it is concluded that the propagation goes through the foliage at frequencies close to 900 MHz for distances up to approximately 1000 m. After this point, the propagation changes to an over the top and then back down again path.

A comparison of foliage excess loss models shows that most of them overestimate the excess loss at distances exceeding a few hundred meters through the foliage. This common for the models based on empirical data related to only short propagation distances through the foliage. This means that they do not predict the extremum as found in the conducted measurement over a longer distance. Two existing models are however found to include an extremum, the ITU-R P.833-9 (Attenuation in vegetation) and ITU-R 2108-0 (Prediction of clutter loss).

Combining the two-ray path-loss model with the ITU-R P.833-9 model, in the best case, gives an RMS error of 14.3 dB and with the ITU-R 2108-0 model 15.8 dB. Combining with the ITU-R P.1546 (Point-to-area predictions for terrestrial services) path-loss model, in the best case, gives an RMS error of 12.3 dB for ITU-R P.833-9 model and 14.3 dB for ITU-R 2108-0 model, respectively.

However, the error for the predicted path-loss obtained from the combined models is, in the worst case, more than 28 dB. As an attempt to improve the model, applying two times clutter loss together with the two-ray and ITU-R P.1546 path-loss model results in a worst case RMS error of 8.1 dB and 11.2 dB, respectively. The additional clutter loss can be argued to be a result of both the transmitter and the receiver being surrounded by foliage, resulting in clutter loss at both ends of the link.

An alternative to the ITU models has been proposed by Tewari et. al. which includes the excess loss due to foliage. This model has also been compared to the measured data and it turns out that the model could predict the path-loss with an RMS error of less than 10.2 dB.

The measurement data also proves that there is no significant difference in received power for the antenna height combinations Tx 1.5 m to Rx 1.5 m and Tx 3.5 m to Rx 2.5 m. Hence, the ITU-R P.1546 path-loss model predicting a minimum of difference between the two height combinations is the best choice. However, for the scenario presented in this work the combination between clutter loss and the two-ray model, in some cases, showed a better fit with the data.

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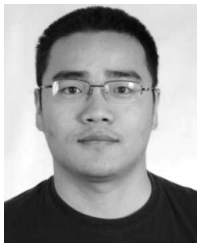


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also the Head of the Doctoral School on Wireless Communication with some 100 Ph.D. students enrolled. He has published more than 175 peer-reviewed papers, and he holds 28 patents. His research interests include radio communication for mobile terminals, especially small antennas, diversity systems, propagation, and biological effects. He has also worked as a consultant for developments of more than 100 antennas for mobile terminals including the first internal antenna for mobile phones in 1994 with lowest SAR, first internal triple-band antenna in 1998 with low SAR and high TRP and TIS, and lately various multi-antenna systems rated as the most efficient on the market. He has worked most of the time with joint university and industry projects and has received more than U.S. 12 M indirect research funding. At present, he is the project leader of the SAFE Project with a total budget of U.S. 8 M investigating tunable front end, including tunable antennas for the future multiband mobile phones. He has been one of the pioneers in establishing over-the-air (OTA) measurement systems. The measurement technique is now well established for mobile terminals with single antennas and he was chairing the various COST groups (swg2.2 of COST 259, 273, 2100 and ICT1004) with liaison to 3GPP for OTA test of MIMO terminals. Presently, he is involved in MIMO OTA measurement.

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